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Experimental Study on Using the Aluminum Sacrificial Anode as a Cathodic Protection for Marine Structures

A. Radwan, A. Elbatran, A. Mehanna, M. Shehadeh

Abstract**—**The corrosion is natural chemical phenomenon that is applied in many engineering structures. Hence, it is one of the important topics to study in the engineering research. Ship and offshore structures are most exposed to corrosion due to the presence of corrosive medium of air and the seawater. Consequently, investigation of the corrosion behavior and properties over ship and offshore hulls is one of the important topics to study in the marine engineering research. Using sacrificial anode is the most popular solution for protecting marine structures from corrosion. Hence, this research investigates the extent of corrosion between the composite ship model and relative velocity of water, along with the sacrificial aluminum anode consumption and its degree of protection in seawater. In this study, the consumption rate of sacrificial aluminum anode with respect to relative velocity at different Reynold's numbers was studied experimentally, and it was found that, the degree of cathodic protection represented by the cathode potential at a given distance from the aluminum anode was decreased slightly with increment of the relative velocity.

Keywords**—**Corrosion, Reynold's numbers, sacrificial anode, velocity.

I. Introduction

NOWADAYS, corrosion in marine structures is one of the most relevant problems in ship and offshore construction and maintenance. Corrosion is defined as the deterioration of a material, usually a metal, because of a reaction with its environment and which requires the presence of an anode, a cathode, an electrolyte, and an electrical circuit [1]-[3]. Since, seawater has significant effect on marine vessels and offshore steel structures because it is highly corrosive media, which leads to the formation of different types of corrosion cells such as dissimilar metal corrosion cells and differential aeration cells. Dissimilar metal cells arise because of the contact between iron grains and the nobler cementite grains (Fe^3C) [2], [3]. For example, dissimilar metal cells (bimetallic corrosion) arise as a result of the contact between the nobler bronze propeller and the less noble steel ship hull. Differential aeration cells arise when part of the marine structure is coated with marine fouling organisms which hinder dissolved oxygen access to the underlying steel. Moreover, the steel marine structure may suffer from differential strain cells at weld lines, stray current corrosion, during welding and bacterial corrosion in polluted harbors [4].

Generally, protection of metals in seawater is obtained by making the structure work as a cathode with impressed current (electrolytic cell) or by coupling to a less noble metal (galvanic cell). Sacrificial anodes have become a standard practice for the protection of vessels and offshore hull structures against corrosion [5]. The sacrificial anode method is preferentially used in seawater, with based alloys of aluminum, zinc or magnesium [6]. Sacrificial cathodic protection is carried out by connecting the marine structures to less noble metal, while impressed current cathodic protection is carried out by connecting the structure to the –ve pole of a direct current power supply, an insoluble anode such as platinized titanium, graphite or oxide coated titanium connected to the +ve pole of the direct current power supply completes the circuit [7].

Many researchers [6]-[19] presented sacrificial anodes as a cathodic protection against corrosion of marine and offshore structures. They studied the aspects of cathodic protection such as the performance of different anode materials, the effect of organic coatings on cathodic protection, and cathodic protection problems such as overprotection and stray current, mathematical modeling of cathodic protection. They also studied the cathodic protection performance in ballast water tanks. Moreover, the effects of environmental conditions on the corrosion and corrosion-erosion rate in offshore pipelines were studied [20]-[24].

This research studied the effect of relative velocity of ship and aluminum anode consumption and potential distribution during sacrificial cathodic protection. This would assist the marine engineers to develop design and economic usage of sacrificial cathodic protection method in different marine structures.

II. Experimental Apparatus

Fig. 1 shows the experimental apparatus used in the present work, it consisted of a horizontal rectangular open plastic channel having the dimensions 60x30 cm for the base and 50 cm for the height. The plastic channel was connected to a plastic storage tank having a base of 80x60 cm and a height of 40 cm filled with 150 m^3 of seawater (3.5% NaCl). Stainless steel centrifugal pump of 1.5 hp was used to circulate seawater between the storage tank and the channel. A steel ship model, shown in Fig. 1 was fixed firmly in the middle of the flow

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channel at a distance of 32 cm between the ship bottom and the channel base. The steel ship model had a length of 33.7 cm, a maximum width of 13 cm and a height of 10.5 cm.

A height of 8 cm of the model of ship was submerged in seawater during experiments. Ball valve was used to control the water flow rate from the storage tank to the channel by means of a graduated cylinder and a stopwatch. In order to determine the rate of sacrificial aluminum anode consumption, a rectangular thin aluminum coupon measuring 3.15x1.2x0.2 cm was fixed to the middle of the submerged part of the ship hull model by means of a steel screw thread.

Before each run, the aluminum coupon was weighted accurately using analytical balance while the steel ship model was treated with emery paper to remove any oxides from the ship surface. The aluminum coupon was fixed to the ship model and then solution was allowed to flow from the storage tank to the channel containing the ship at the required flow rate for a time of 1 hour. At the end of the experiment, the aluminum coupon was dismantled, washed with fresh water then dried and reweighed.

The rate of aluminum consumption "*R*" during cathodic protection was calculated from:

$$R = \frac{loss\ \ in\ \ weight\ (m)}{coupon\ \ area \times time} \quad in\ g/cm^2 \cdot \min \tag{1}$$

In order to study the cathode potential distribution and the degree of cathodic protection at different distances from the aluminum coupon in the horizontal and vertical direction, the potential difference between the ship hull at different locations and an Al/AlCl electrode was measured by means of a high impedance voltmeter as shown in Fig. 2.

The reference electrode was placed in the cup of a glass lugging tube whose tip was placed at 0.5 mm from the location whose potential is to be measured; the lugging tube was filled with seawater [25]. The specifications and material compositions of aluminum anode used in the present study are shown in Table I which is used in practical cathodic protection [26], [27].

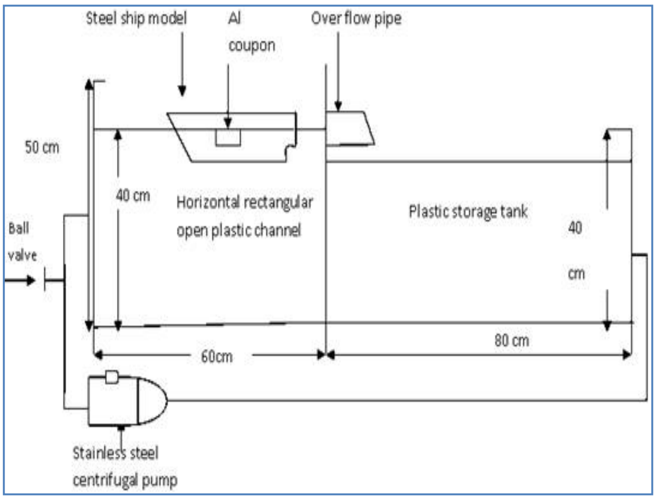

Fig. 1 Experimental apparatus components in horizontal view

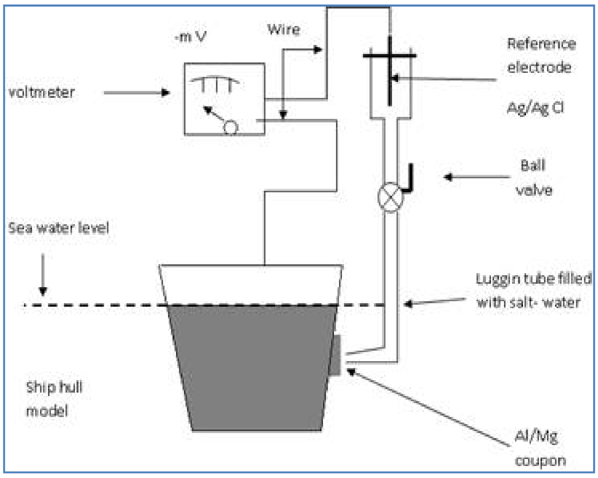

Fig. 2 Electrical circuit with voltmeter

TABLE I
SACRIFICIAL ANODE MATERIALS AND THEIR PROPERTIES USED IN THE PRESENT STUDY

PROPERTY	Aluminum alloy
Percent composition	Cu: <0.006 Fe: <0.1 Hg: 0.02 - 0.05 Si: 0.11 - 0.21 Zn: 0.3 - 0.5 Others: each <0.02 Al: remainder
Density /kg m^{-3}	2695
Capacity /A h kg^{-1}	2640
Wastage by weight /kg A h y^{-1}	3.2
Wastage by volume /ml A y^{-1}	1180
Output / A m^{-2}	6.5
Voltage range of metal vs. reference electrode (mV)	-700 To -900

III. GOVERNING EQUATION

The effect of Reynolds number and seawater velocity on the rate of aluminum anode consumption are described as:

- For low Re <3500

$$R= 5.44*10^{-6}*Re^{0.5046} \tag{2}$$

with an average deviation of ± 0.171%.

- For high Re > 3500

$$R = 2.449*10^{-9}*Re^{1.465} \tag{3}$$

with an average deviation of ± 0.00107 % where

$$Re = \frac{\rho\ V\ d_e}{\mu} \tag{4}$$

V is the solution velocity in cm/s, it was obtained by dividing the volumetric flow rate of the solution by the wetted cross sectional area of the flow channel; ρ, μ are the density and viscosity of seawater in gm/cm^3 and poise respectively. The d_e is the equivalent diameter of the duct containing the ship; it was calculated from

$$d_e = \frac{4 * \text{cross sectional area of the duct - ship wetted area}}{\text{perimeter of the duct - deck of ship wetted perimeter}} \quad (5)$$

IV. RESULTS AND DISCUSSIONS

Fig. 3 shows the effect of Reynolds number on the rate of aluminum anode consumption. It was noticed that the consumption of aluminum anode increased with the increment of Reynolds number. The relation between the sea water velocity and the sacrificial anode consumption is displayed in Fig. 4. It can be observed that the effects of the sea water velocity on the consumption rate of the anode decreased at the lower values of the velocity, in contrast, the consumption rate increased with the increasing in the velocity.

The increase in the rate of aluminum consumption with solution velocity and Re can be explained as: Sacrificial cathodic protection of the steel ship hull with aluminum anode takes place through the galvanic cell Al/seawater/steel, the cell reactions are:

Anode (Aluminum): $Al \xrightarrow{\quad} Al^{++} + 2e$

Cathode (steel): $\frac{1}{2} O_2 + H_2O + 2e \xrightarrow{\quad} 2OH^-$

Kinetic studies of above reactions have revealed that galvanic corrosion of aluminum in the above cell is controlled by the cathodic reduction of dissolved oxygen at the steel surface [25], the slowness of the cathodic reduction of dissolved oxygen is attributed to the slowness of the diffusion of dissolved oxygen from the solution bulk to the cathode (steel) surface [25] across the diffusion layer surrounding the ship hull [28]. Increasing the solution velocity past the ship hull decreases the thickness of the hydrodynamic boundary layer and the diffusion layer [28] with a consequent increase in the mass transfer coefficient K (k=D/δ) and dissolved oxygen flux N according to

$$N = K\,CO_2 \quad (6)$$

where N= flux of dissolved oxygen, mole/cm^2.s, K is the mass transfer coefficient, cm/s, CO_2 is the concentration of dissolved oxygen in seawater, mole/cm^3, D is the diffusivity of dissolved oxygen in cm^2/s. The considerable increase in the rate of aluminum consumption for Re >3500 may be attributed to the transfer of flow around the ship model from the laminar flow regime to the turbulent flow regime [28]. It is noteworthy that the rate of aluminum dissolution increases by a maximum of 22.4% and 167.1% under laminar and turbulent flow respectively compared to the case of no flow (stagnant conditions).

Figs. 5-8 show the anode curves of typical potential versus distance at V = 0 (stagnant solution) and V = 85 cm/min respectively. The effect of different solution velocities on the magnitude of the cathode potential at a horizontal distance 10 cm and a vertical distance of 2.5 cm from the anode respectively also are illustrated.

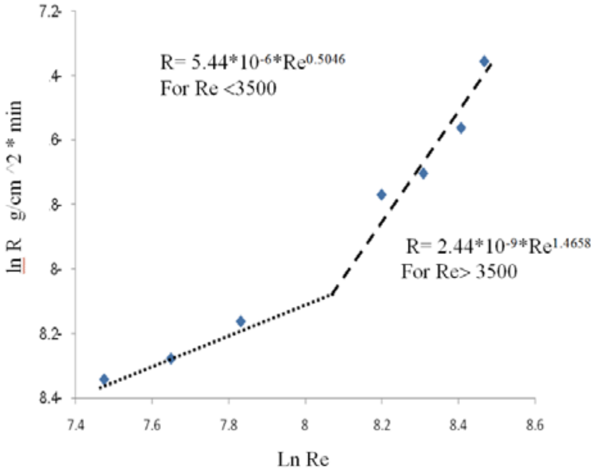

Fig. 3 Effect of Reynolds number on the rate of aluminum anode consumption

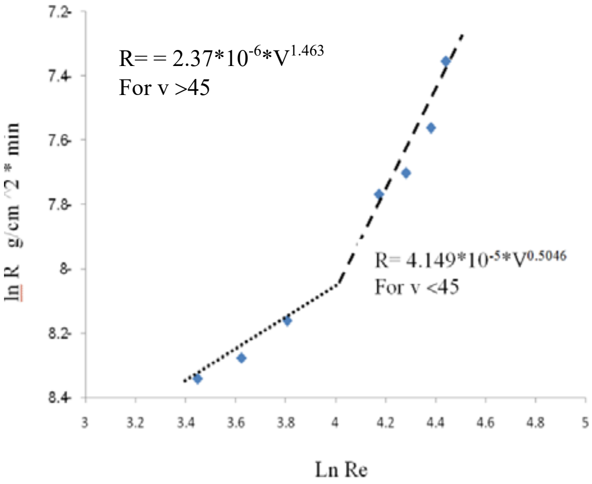

Fig. 4 Effect of seawater velocity on the rate of aluminum anode consumption

The results showed that within the present range of experimental conditions, the degree of cathodic protection decreased slightly with the increasing in distance of the aluminum anode. It can be also seen that the degree of cathodic protection increased slightly with decreasing in solution velocity in the horizontal and vertical directions. The decreased in cathode potential with distance and solution velocity was attributed to the increment in the ohmic drop IR. Moreover, when the distance between the aluminum anode and the cathodic location was increased, the resistance R between the cathode and anode was also increased. As the solution velocity increased, the flux of dissolved oxygen increased towards the cathode surface. With a conquest increase in the dissolution current (I) according to [29]:

$$\frac{I}{ZF} = KAC_{O_2} \quad (7)$$

where A is the cathode area in cm^2; I is the dissolution current in Amperes. This increasing in the dissolution current of Al was due to increase the IR drop between the Aluminum anode and the steel cathode at any distance from the anode with a consequent decreased in the cathode potential and the degree of cathodic protection.

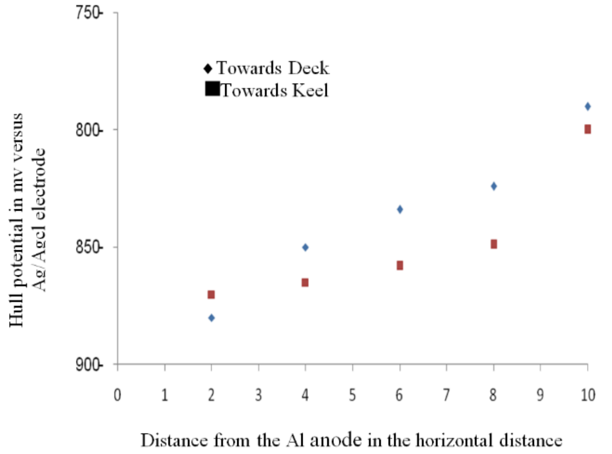

Fig. 5 Potential distribution in horizontal direction (X) towards bow and stern the ship model vs. Ag/Ag Cl ref. electrode by V_0

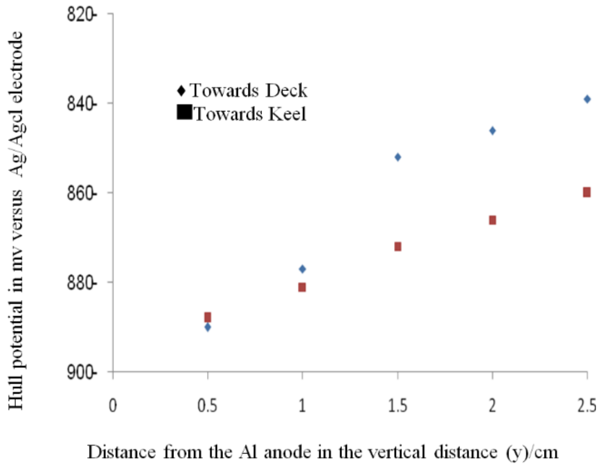

Fig. 6 Potential distribution in vertical direction (Y) towards keel

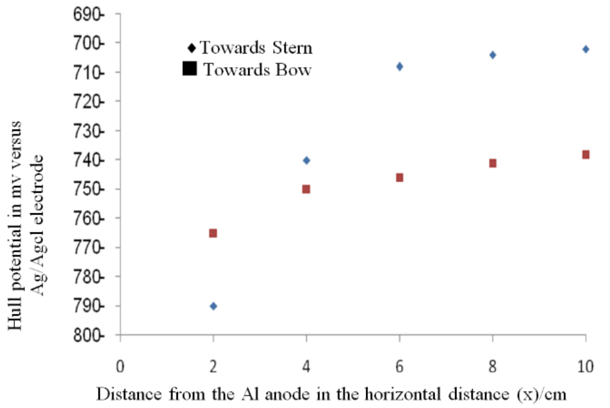

Fig. 7 Potential distribution in horizontal direction (X) towards bow and stern the ship model vs. Ag/Ag Cl ref. electrode by V

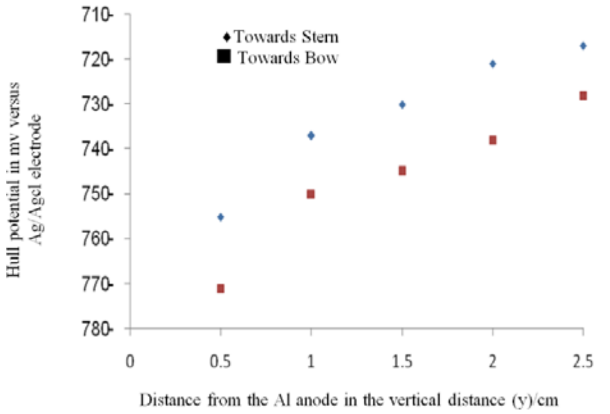

Fig. 8 Potential distribution in vertical direction (Y) towards keel and deck the ship model vs. Ag/Ag Cl ref. electrode by V

V. CONCLUSIONS

The present results have shown that the amount of aluminum required to protect a marine vessel for a given period of time depends on the relative motion between the marine vessel and seawater. Within the present range of conditions, the amount of aluminum needed to protect a moving marine vessel exceeds that of a stagnant marine vessel by an amount ranging from 22.4% to 167.1% depending on the velocity of the marine vessel. It was also found that the relative velocity between the marine vessel and seawater affects potential distribution on the vessel and the degree of cathodic protection at locations far from the aluminum anode; the higher the relative velocity the lower the cathode potential and the degree of cathodic protection at a given location. The present results call for further studies covering a wider range of experimental conditions which simulates practical conditions where higher relative velocities are used.

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